

HAWAII GEOTHERMAL PROJECT

ENGINEERING PROGRAM

PROGRESS REPORT

JANUARY 1, 1975 TO AUGUST 31, 1975

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By

Hi Chang Chai
Bill Chen
Ping Cheng
James Chou
Deane Kihara
Kah Hie Lau
L. Stephen Lau
Patrick Takahashi
Paul Yuen

Hilo College
University of Hawaii
Hilo, Hawaii 96720

College of Engineering
University of Hawaii
Honolulu, Hawaii 96822

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INTRODUCTION

The objectives of the Engineering Program are (1) applied research in problem areas related to the extraction of energy from geothermal resources, and (2) planning, design, and specification of a research-oriented, environmentally-acceptable geothermal power plant. Work is progressing on two tasks:

Task 3.1 Geothermal Reservoir Engineering

Task 3.6 Optimal Geothermal Plant Design

This report summarizes the timetable (A) for each task, the progress made to date (B), and the future work planned (C).

TASK 3.1 GEOTHERMAL RESERVOIR ENGINEERING

A. Timetable

1. Numerical Modelling of Geothermal Reservoirs

Investigators: P. Cheng, K. H. Lau, and L. S. Lau

- | | |
|-------------------|--|
| May 31, 1975 | <ol style="list-style-type: none">1. Complete numerical solutions for heat transfer and fluid flow characteristics in an axisymmetric geothermal reservoir2. Complete numerical solution of steady state pumping in a confined geothermal reservoir |
| August 15, 1975 | <ol style="list-style-type: none">1. Complete numerical solution of steady reinjection in a confined geothermal reservoir2. Formulate problem of transient responses in geothermal reservoirs with pumping and reinjection |
| December 31, 1975 | <ol style="list-style-type: none">1. Complete numerical solution of steady state pumping and reinjection in unconfined geothermal reservoirs2. Complete finite element solution of free convection in a two-dimensional geothermal reservoir with irregular geometry (linear model)3. Initiate numerical solution of the effects of geothermal heating on Ghyben-Herzberg lens |

2. Well Test Analysis and Physical Modelling

Investigators: B. Chen, L. S. Lau, and P. Takahashi

- | | |
|----------------|---|
| April, 1975 | <ol style="list-style-type: none">1. Complete literature survey2. Continue correspondence with U.S. and New Zealand researchers to acquire geothermal reservoir data3. Develop well test and analysis methodology4. Initiate computer program to combine type curve matching and mass/energy balance5. Continue fabrication of preliminary unpressurized physical model |
| June, 1975 | <ol style="list-style-type: none">1. Send preliminary well test procedure plan to H. Ramey (Stanford) and R. Kingston (New Zealand)2. Obtain quotation for equipment costs, on site measurement, and analysis of results of one geothermal well3. Initiate physical model tests |
| August, 1975 | <ol style="list-style-type: none">1. Interact with drilling manager on logging, coring, drill stem testing and well head completion hardware and techniques2. Complete manuscript--"Update on the State-of-the-Art in Geothermal Reservoir Engineering"3. Continue laboratory runs on unpressurized physical model and fabricate pressurized model |
| October, 1975 | <ol style="list-style-type: none">1. Order well measurement equipment2. Complete unpressurized model tests and initiate pressurized model tests |
| December, 1975 | <ol style="list-style-type: none">1. Complete computer program capable of predicting geothermal reservoir performance2. Arrange to regularly visit drill site and confer with drilling manager3. Complete preliminary physical model tests |
| June, 1976 | <ol style="list-style-type: none">1. Initiate series of drawdown, buildup and water injection tests after well completed2. Predict well performance3. Analyze data of model studies and design final pressurized physical model |

TASK 3.1 GEOTHERMAL RESERVOIR ENGINEERING

B. Progress to Date

Research work in the areas of numerical modelling, physical modelling, and well analysis are continuing. A summary of work done during Phase I of the grant is reported in Reference [1].*

1. Numerical Modelling of Geothermal Reservoirs

During the past seven months, the following three problems have been investigated.

a. Effects of Steady Withdrawal of Fluids in Confined Geothermal Island Aquifers

Consider an island aquifer confined by caprock on the top, heated by an impermeable surface at the bottom, and recharged continuously from the ocean (see Fig. 3.1-1). If a production well is located in the confined aquifer, it will be of interest to investigate the effects of the location of the well and the withdrawal rate on heat transfer and fluid flow characteristics in the aquifer.

The formulation of the problem is given in Reference [2] where the governing non-linear partial differential equations are expressed in terms of dimensionless dependent variables θ and P and independent variables R (or X) and Z . The parameters for the present problem are the modified Rayleigh number, Ra , the aspect ratio, L , and the dimensionless withdrawal rate, Q , which is given by $Q = Q^*/h\alpha$ for a cylindrical reservoir and $Q = Q^*/\alpha$ for a rectangular reservoir where Q^* , h , α are respectively the dimensional withdrawal rate, the height of the reservoir, and the equivalent thermal diffusivity.

Numerical solutions were obtained for $Ra = 500$ and $L = 4$ for the following cases

- 1) A cylindrical reservoir with a sink at $(0, 0.4)$ and with a withdrawal rate of $-25 \leq Q \leq 0$. The prescribed temperatures are $\theta_a = \theta_s = 0$ and $\theta_L = \exp[-(2R)^2]$.
- 2) A two-dimensional rectangular reservoir with a sink at $(0, 0.4)$ and with a withdrawal rate of $-75 \leq Q \leq 0$. The prescribed temperatures are $\theta_a = \theta_s = 0$ and $\theta_1 = \exp[-(2X)^2]$.

*Task 3.1 References are listed on page 27.

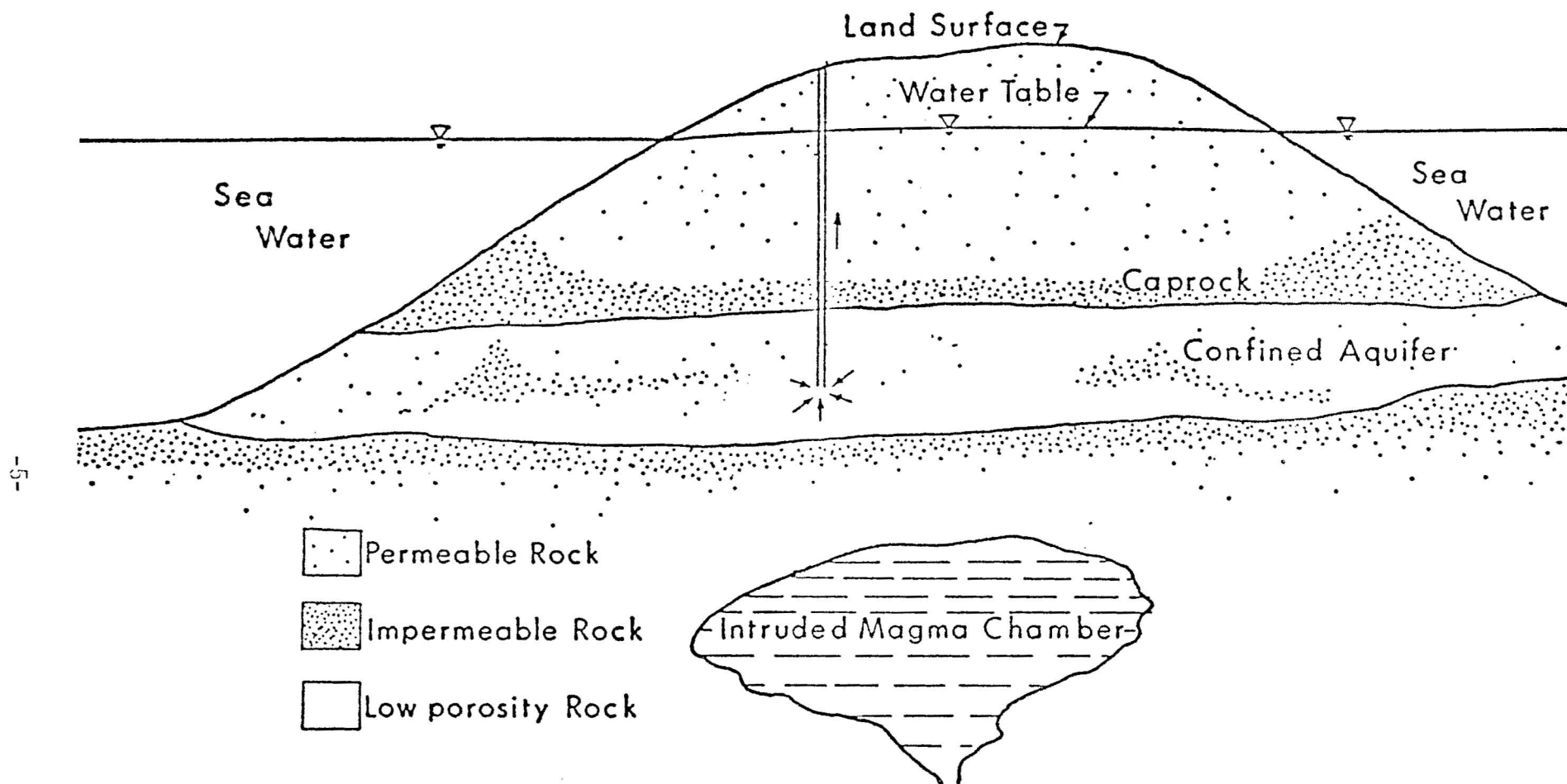


FIGURE 3.1-1 WITHDRAWAL OF FLUIDS FROM A GEOTHERMAL RESERVOIR

- 3) A two-dimensional rectangular reservoir with an off-center sink at $(0.4, 0.4)$. The prescribed temperatures and the magnitude of sink strength are the same as Case 2.
- 4) A two-dimensional rectangular reservoir with two sinks of equal strength at $(\pm 0.4, 0.4)$. The prescribed temperatures and the magnitude of sink strength are the same as Case 2.

Fig. 3.1-2 shows the isotherms in an axisymmetric geothermal reservoir for withdrawal rates of $Q = 0, -2$, and -25 . It is noted that the isotherms begin to show some signs of contraction when the dimensionless withdrawal rate is less than minus one. At $Q = -25$, the isotherm for $\theta = 0.2$ is almost collapsed although the shape for $\theta = 0.8$ is hardly changed.

Fig. 3.1-3 shows the isotherms in a rectangular geothermal reservoir with a line sink at $(0, 0.4)$ for $Q = 0, -25$, and -75 . As in Fig. 3.1-2, the isotherms begin to contract as the withdrawal rate is increased. It should be emphasized that the definitions of the sink strengths for a point sink and a line sink are different and therefore their relative magnitudes cannot be compared.

The unsymmetric isotherms shown in Fig. 3.1-4 are due to off-center withdrawal of fluids in a rectangular reservoir. A comparison of Figs. 3.1-3 and 3.1-4 shows that the rate of collapse of isotherms is faster for the off-center withdrawal of fluids.

Fig. 3.1-5 shows the effect of withdrawal rates on the isotherms in a rectangular geothermal reservoir with two sinks of equal strength, located symmetrically with respect to the heat source. Whereas the isotherms in Figs. 3.1-3 and 3.1-4 are almost collapsed at $Q = -75$, the isotherms in Fig. 3.1-5 do not collapse at twice the withdrawal rate. On the contrary, the extent of isotherms for $\theta = 0.5$ and $\theta = 0.8$ seems to increase as the withdrawal rates are increased.

A detailed discussion of the problem is given in Reference [2], which was presented at the Second U.N. Symposium on Geothermal Resources, San Francisco, California, May 20-29, 1975.

b. Effects of Steady ReInjection of Fluids in Confined Geothermal Island Aquifers

The residual water from a geothermal power plant is usually disposed of through deep reinjection wells. It will be of interest to study the effects of reinjection rate, the location of the reinjection well, and the

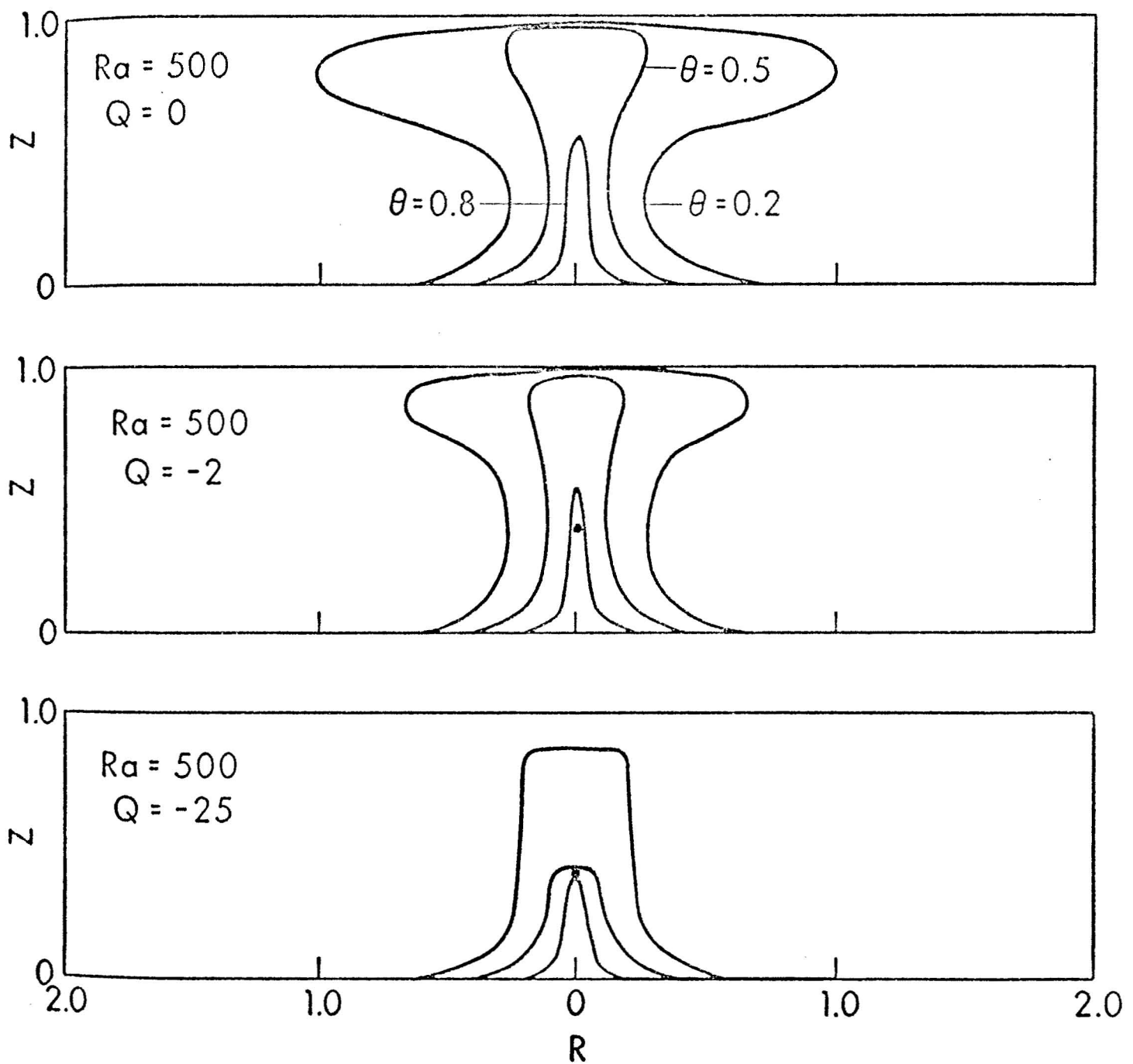


FIGURE 3.1-2 THE EFFECT OF WITHDRAWAL RATES ON ISOTHERMS
IN AN AXISYMMETRIC GEOTHERMAL RESERVOIR

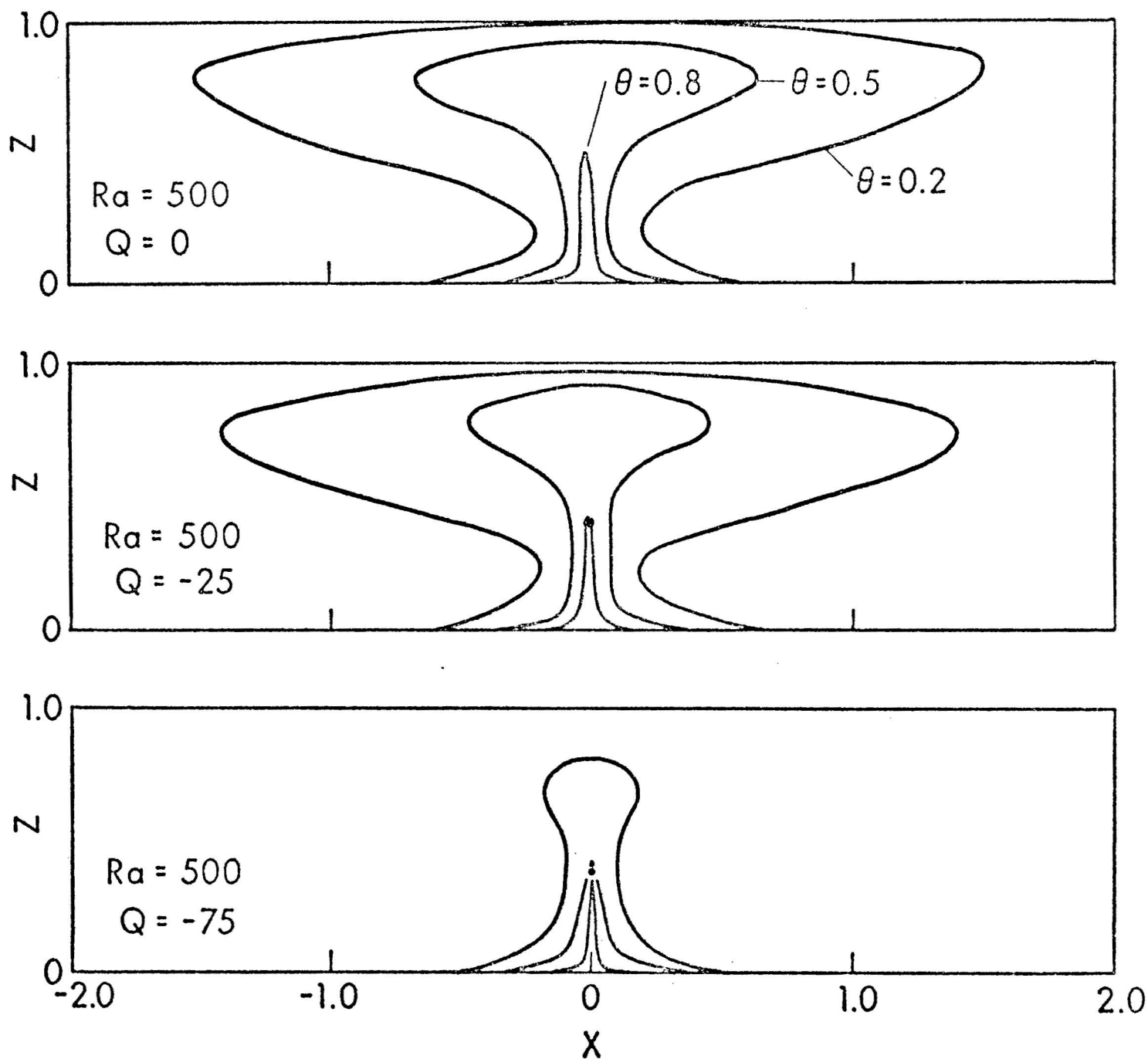


FIGURE 3.1-3 THE EFFECT OF WITHDRAWAL RATES ON THE ISOTHERMS
IN A RECTANGULAR GEOTHERMAL RESERVOIR

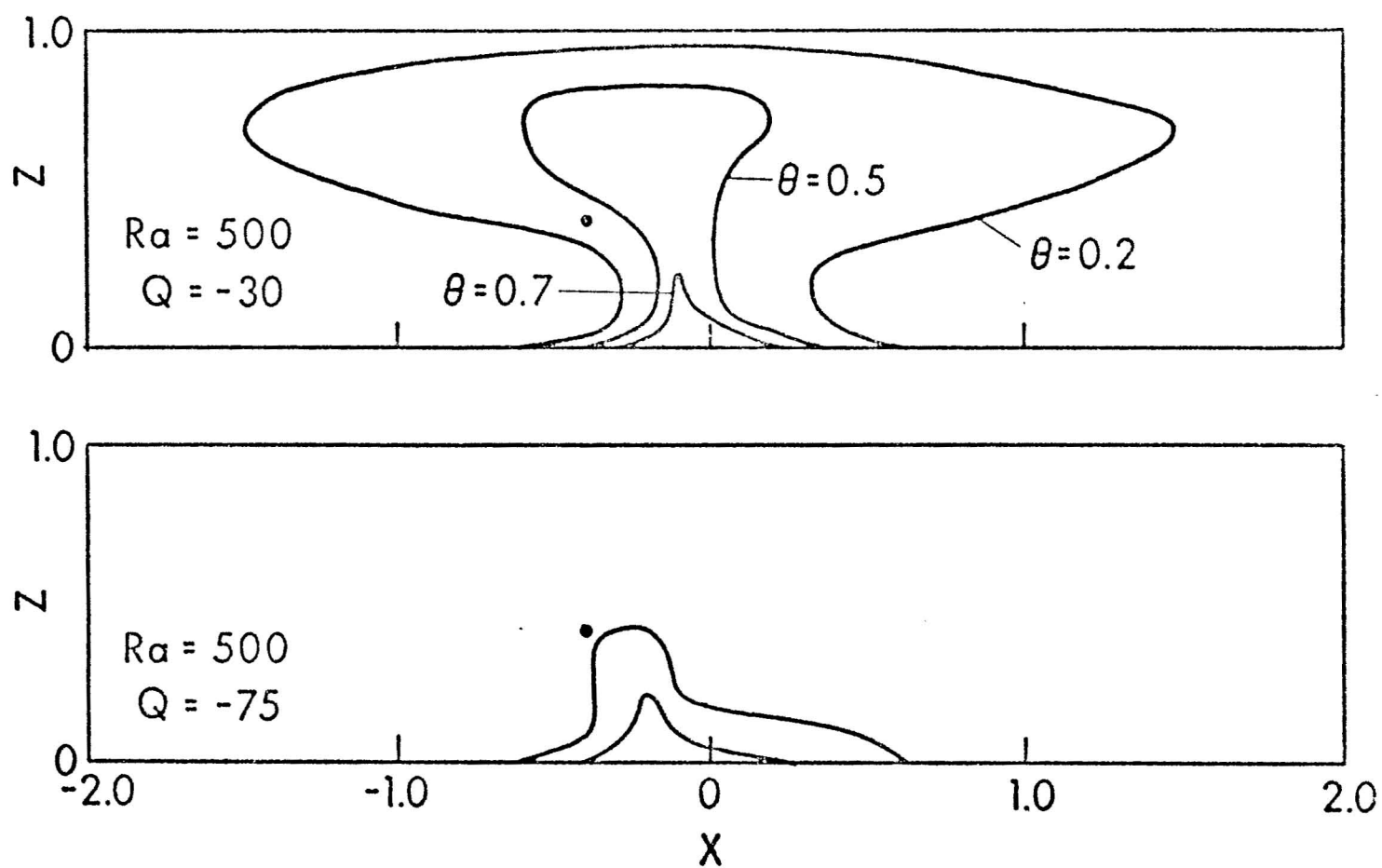


FIGURE 3.1-4 ISOTHERMS IN A RECTANGULAR GEOTHERMAL RESERVOIR WITH OFF-CENTER WITHDRAWAL OF FLUIDS AT DIFFERENT WITHDRAWAL RATES

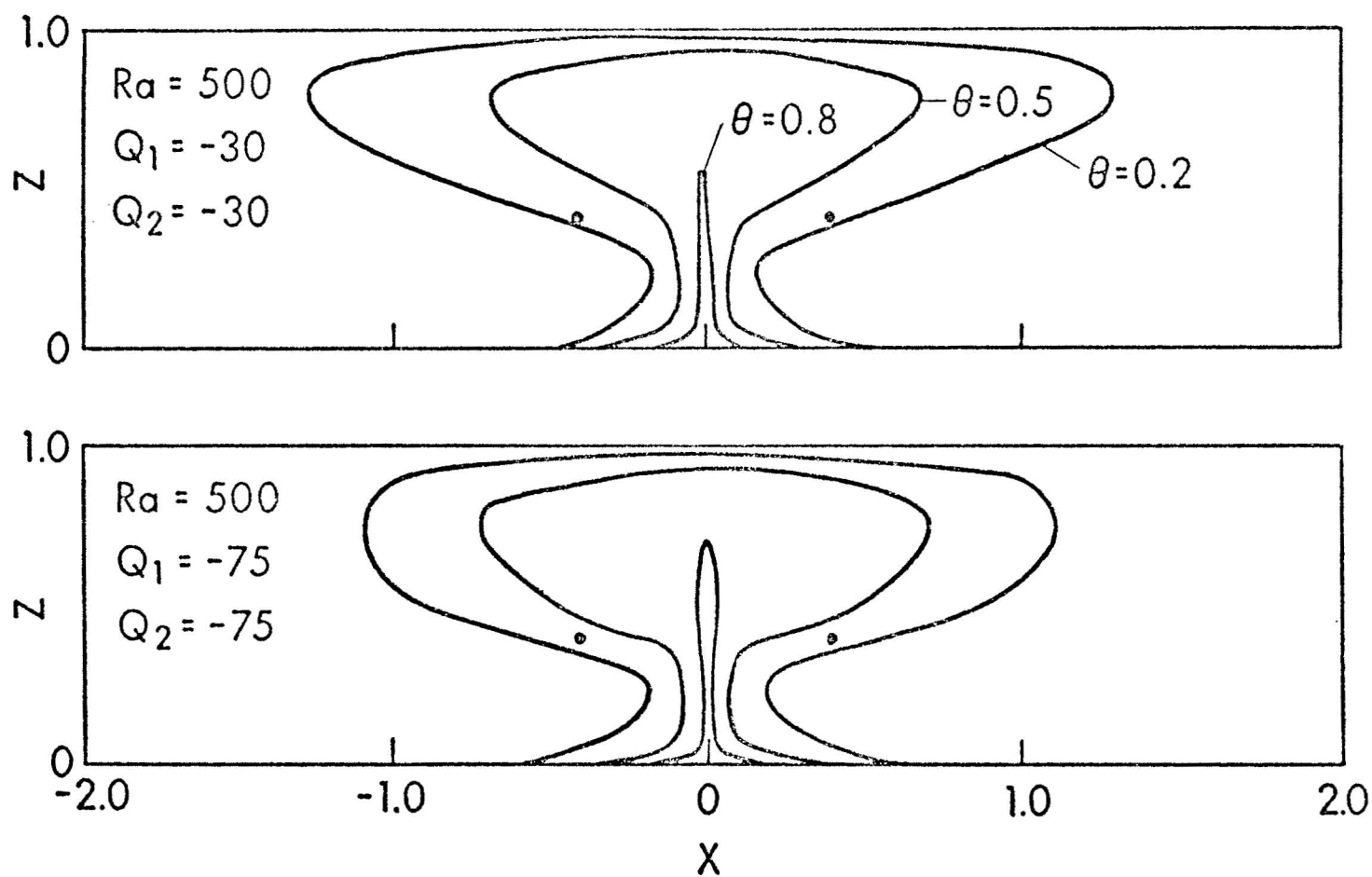


FIGURE 3.1-5 ISOTHERMS IN A RECTANGULAR GEOTHERMAL RESERVOIR WITH TWO SINKS OF EQUAL STRENGTH

temperature of the reinjected fluid on the heat transfer and fluid flow characteristics in the aquifer.

Fig. 3.1-6 shows the effect of reinjection rate on the isotherms in a cylindrical aquifer with $Ra = 300$. The reinjection well is located at $R = 0$ and $Z = 0.5$ where the normalized temperature is equal to 0.76 at zero injection rate. If the temperature of the injected fluid is at 0.4, which is cooler than the corresponding temperature at zero injection rate, a negative buoyancy force is generated which forces the injected fluid to move downward. Thus a portion of the aquifer near the injected well is cooled down. The extent that the aquifer is cooled down depends on the reinjection rate and the temperature of the injected fluid. A detailed discussion of the problem will be reported at a later time.

c. Finite Element Analysis of Free Convection in Unconfined Geothermal Reservoirs

Finite element solutions, taking into account the irregular geometry of the boundaries, have been obtained for free convection in unconfined geothermal reservoirs. Since the perturbation equations given in Reference [3] are used, the formulation is only applicable to reservoirs with low Rayleigh number. A report covering this work is currently under preparation.

2. Well Test Analysis and Physical Modelling

Discussion of previous work accomplished can be found in prior reports to the National Science Foundation and in-house publications [4]. A summary is available in the July 1975 issue of the American Society of Civil Engineering Journal of the Power Division [5].

As most of the work initially outlined for this task has been completed or well laid out, an overview of the main concepts should be useful for perspective purposes. The following is the research to be performed and will essentially form the basis for three master's degree theses:

- An Assessment of Techniques of Testing Geothermal Wells [8]
 - Types of geothermal reservoirs
 - Downhole well test measurement techniques
 - Reservoir analysis during drilling
 - Analysis of well flow characteristics
 - Results of international survey on geothermal reservoir engineering
 - Cost of downhole geothermal well testing equipment

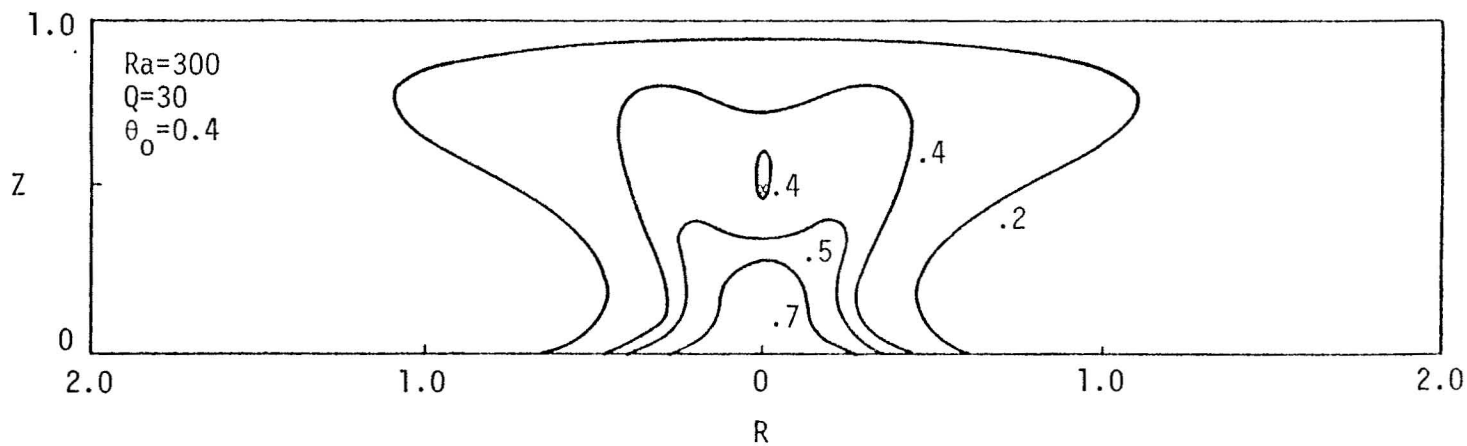
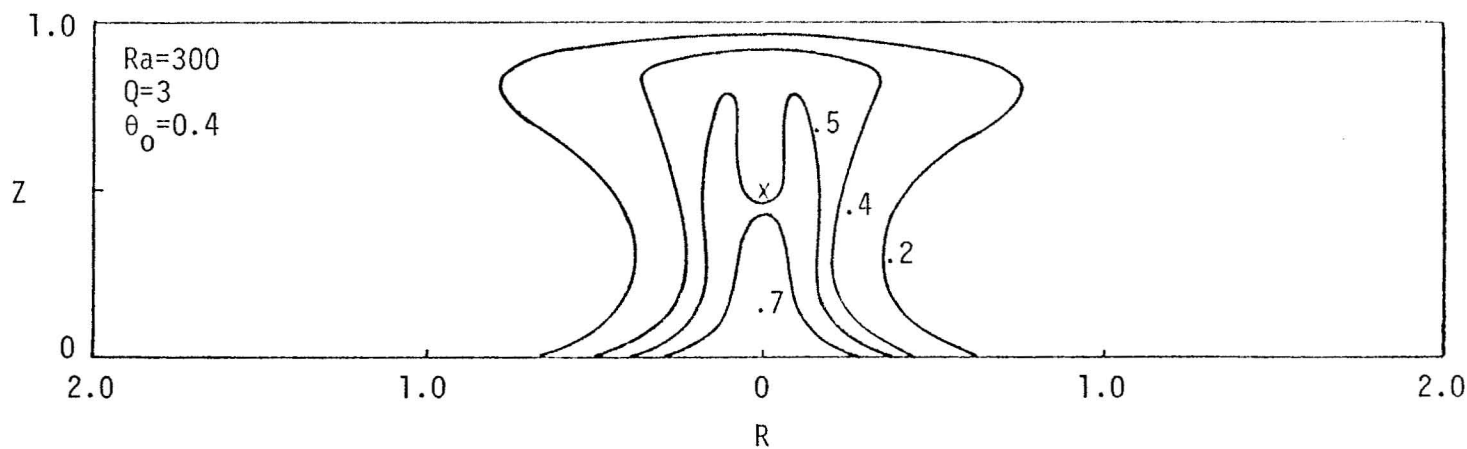
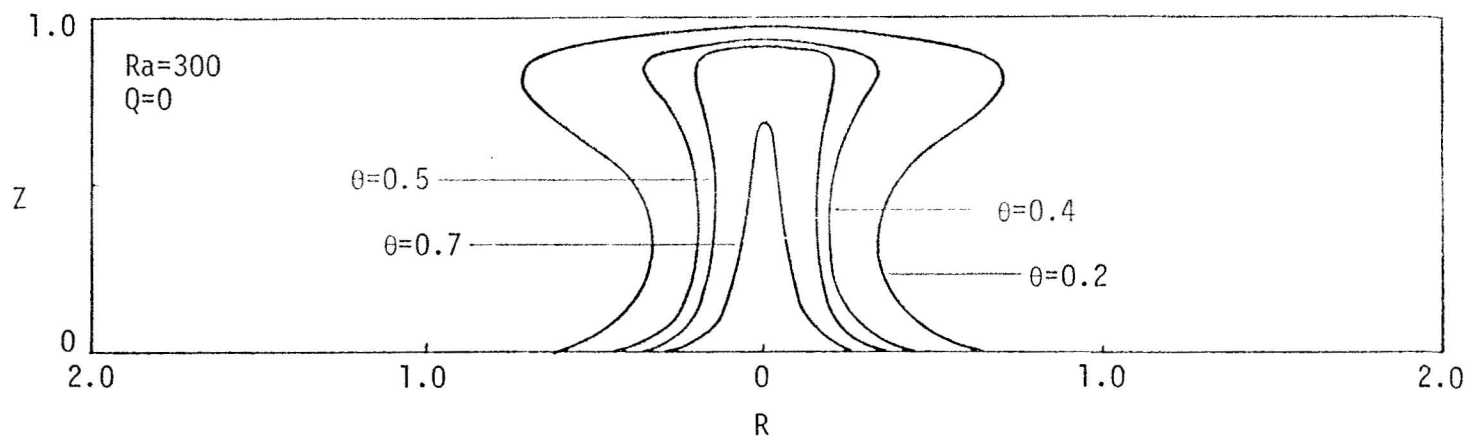


FIGURE 3.1-6 THE EFFECT OF REINJECTION RATES ON ISOTHERMS IN AN AXISYMMETRIC GEOTHERMAL RESERVOIR

- Well Test Analysis
 - Historical work and relation of geothermal to petroleum reservoir engineering
 - Materials/Energy equations
 - Pressure buildup and formation average pressure
 - Water/Steam properties
 - Sensitivity analysis
 - Computer analysis
 - Details on computer program capable of predicting well performance given pressure, temperature, and flowrate over time data
- Physical Modelling of Geothermal Reservoirs
 - Previous laboratory work
 - Dimensional analysis and the Rayleigh number
 - Theoretical computer calculations
 - Physical model design and construction
 - Experimental work
 - Analysis of results and correlation with computer models

a. Well Measurement

Letters of quotation were sent out requesting well hardware and measurement bids. The following summarizes the response:

QUOTATION FOR	LETTERS SENT	NEGATIVE RESPONSES	POSITIVE RESPONSES
Hardware	8	2	4
Measurement/Analysis	14	4	3

Rogers International tendered the following costs of services bid:

Design and Procurement of Well Test Equipment	\$15,000
Well Test Plumbing (downstream of wellhead valve)	\$70,000-\$100,000
Well Testing (3 months)	\$65,000-\$100,000
Well Analysis	\$ 8,000
TOTAL	\$158,000-\$223,000

It was suggested that negotiations be consummated on a cost-plus-services contract rather than on a lump-sum basis.

Robin Kingston (New Zealand) indicated that there was a high probability measurement equipment could be borrowed from the New Zealand government. Further, his (or a colleague's) expertise could be utilized to carry out the testing program.

Schlumberger roughly estimated a per month total cost of equipment lease plus operational manpower of \$40,000 for the measurement phase of the program. The final figure will be dependent on factors such as prior contracting for well logging services during drilling.

If Kuster mechanical instruments are purchased for downhole tests, the equipment costs would amount to \$16,500. Salary, travel, per diem, and training costs for a three-month period could range from \$15,000 to \$30,000, depending on the number of people involved and the degree of training. The advantages of this latter means of handling well testing are: 1) trained personnel will be available in-state, and 2) some continuity is required to tie in with the well analysis program.

We presently plan to conduct the well testing program in the following manner:

- 1) Negotiate with Robin Kingston and the New Zealand government for loan of measurement equipment or purchase Kuster downhole instruments for \$16,500. Also required in the latter is the purchase of instrumentation, the cost of which should not exceed \$5,000.
- 2) Seek advice from R. Kingston on wellhead plumbing design. Purchase equipment; the cost will be about \$70,000, with the separator being a major part of this expense. A second alternative would be to work out an arrangement with Rogers International for a service contract. The cost would be in the area of \$100,000.
- 3) If it is determined that geothermal fluids are present, follow up on a crash training program for two members of the Hawaii Geothermal Project. New Zealand has indicated a willingness to cooperate at no fee. The cost is estimated to be \$12,000 for travel, per diem, and salary.
- 4) Conduct well tests under the part-time supervision of Robin Kingston or his company's representative. The cost for a three-month period could range from \$15,000 to \$25,000. If Kingston or his representative is not available, a service fee can be negotiated

with Rogers International. The cost will be higher . . . perhaps double.

- 5) Reservoir performance prediction can be accomplished within the Hawaii Geothermal Project with the initial assistance of Hank Ramey.

In short, a complete well test and analysis program as recommended, could range in cost from \$100,000 to \$160,000. Tests of subsequent wells could then be accomplished at operational manpower rates, if all instrumentation and surface plumbing downstream of the wellhead valve are made available.

The well measurement program should occur in the following sequence:

- 1) Evaluate Preliminary Formation Potential

After each drill stem test, data will be analyzed to determine whether or not to complete the well. These tests will also be used to decide whether the well needs to be drilled further to a greater depth. Furthermore, such tests will also provide important information, as, for example, chemical content of the formation fluid, theoretical and actual productivity indexes (PI), reservoir pressure and temperature and the amount of wellbore damage [6,7].

Certain factors will be used to decide whether a particular well should be completed. They are reservoir temperature, reservoir pressure, salt content of the fluid and the productivity indexes.

Normally, the actual PI [4,7] is lower than the theoretical PI. A high actual PI shown by a given well will be one of the deciding factors in favor of completing that well. In all probability, the well should be abandoned if the theoretical PI is low; but if the theoretical PI is high, chances for stimulating the well are still good (either by removal of the skin surrounding the well bore or by further penetration of the productive zone) [6].

Another important criterion is the fluid condition. It is widely accepted that conventional steam turbine technology constrains the reservoir temperature of a producible geothermal well to be above 180°C. Furthermore, the salt content of the geothermal fluid will be a deciding factor as to the method of drawing the fluid. For example, extremely high solids content fluids will more likely be pumped under pressure.

2) Select Well Completion Methods and Surface Plumbing Facilities

If the drill stem tests show favorable reservoir conditions, then the well should be completed for further testing. Various methods, such as perforated casing, slotted liner, commercial well screen and gravel packing will be considered. One or a combination of the above will be chosen. Specific methods will be decided after properties of the borehole are thoroughly evaluated. It should be noted that the steam wells in the Geysers are not completed at all [8,9].

There is strong reason to believe, from geophysical data, that the geothermal wellhead fluid will be a mixture of steam and water (two-phase or flashed-flow). For the ensuing discussion, the above fluid condition has been assumed. In the event of superheated fluid condition, equipment requirements will be simplified.

Surface plumbing facilities will include wellhead valve assembly, separator (for flashed-flow fluids) and silencer. The recommended separator, which has been successfully employed at Wairakei, is the centrifugal cyclone separator [10,11]. This type of separator claims an efficiency of 99.9 percent. The current state-of-the-art of flow measurement does not allow one to obtain accurate information on two-phase flow. Therefore, a separator is needed to separate the liquid from the steam. Then, separate flow meters and calorimeters will be used to obtain enthalpy and flowrates.

3) Initiate Drawdown and Buildup Tests

These tests are basically downhole pressure measurements. A series of alternate drawdown and buildup tests should be conducted to gain information on permeability thickness, porosity thickness, skin effect, wellbore storage, formation average pressure and productivity indexes.

It is suspected that the downhole reservoir pressure will be no greater than the equivalent hydrostatic pressure in Hawaii's geothermal reservoir. Therefore, the well may be started by injecting compressed gas (air, nitrogen or carbon dioxide) to induce the hot liquid up to the surface. It is also probable that

due to economic reasons, one cannot completely shut down the well; thus, two-rate buildup tests must be performed.

Conventionally, after well completion, a resting period approximating one month is practiced to enable underground conditions to stabilize. If hands-on experience at well testing is not acquired prior to well completion, it is imperative that on-site training be accomplished at this time. New Zealand officials have indicated that arrangements can be made to obtain such training.

There are potential hazards associated with well testing. For example, noxious gases could concentrate in the drilling cellar, high noise levels will occur at the discharge, and high temperature/pressure fluids may cause bodily harm. Therefore, safety policies need to be established and maintained.

4) Initiate Temperature Measurements

Temperature measurements vs. the drilled hole depth can reveal information such as conductive and convective zones, high or low permeability zones, etc. A temperature measurement conducted right after a well is shut can also reveal whether any local aquifer inflow exists.

The instruments that have been successfully used at various geothermal sites are the "geothermograph" [10,12], thermistor, and the Amerada-Kuster RPG Temperature Gage. The particular selection of the instrument will depend on the reservoir condition and results of the equipment survey.

5) Estimate Wellbore Heat Losses

By simultaneously measuring the downhole and wellhead conditions, one can estimate the wellbore heat losses. In the future, then, downhole reservoir conditions can be approximated by wellhead measurements, which are easier and more economical to run.

Success at planning and conducting well measurement tests increase with hands-on experience. Initial tests will require the supervision of a seasoned instrumentation engineer.

b. Well Analysis

The well analysis phase is in the process of final development and will take the form of a computer program capable of predicting well performance given pressure, temperature and flowrate over time, plus certain geological parameters such as permeability, porosity, etc. The code will be effective for any combination of fluid properties: compressed hot water, saturated hot water, two-phase fluid (steam plus water at the full spectrum of steam quality), steam, and superheated steam. Extensions will be optional for the presence of non-condensable gases and dissolved solids (primarily chlorides, silicates, carbonates and sulfates up to 35% by weight).

The search for geothermal data to test the computer program for predicting future performance of a geothermal reservoir was difficult. This information is treated as proprietary information by private firms operating geothermal reservoirs. Therefore, communication was directed to New Zealand. Five reels of microfilm containing geothermal data were received, compliments of Dr. James Mercer, U.S.G.S., who obtained the data from New Zealand.

The software effort of developing a computer program for predicting the future performance of a geothermal reservoir using the mass-energy balance equations is nearing completion. The conditions under investigation range from 300°F to 600°F, and 67 to 1543 psia. Thus far, preliminary sensitivity investigations have begun varying initial mass and steam quality with changing temperatures. Other parameters will also be checked.

The program will be tested using part of the New Zealand data. After all states have been covered, a sensitivity check on different parameters of the mass-energy balance equation will be made.

Details on the theory behind the computer program can be found in Reference [4]. Using the pressure measurements obtained from the series of drawdown and buildup tests, one will be able to get information on effective permeability thickness, effective porosity thickness, wellbore skin effect, wellbore storage coefficient, formation average pressure and productivity indexes. These can be achieved by applying the type curve analyses and standard pressure buildup analyses [4,7,13]. Depending on the length of the production of the well, one may get data points on the formation average pressure vs. cumulative production information. With the heat-materials

balance equation one will be able to estimate initial volume, pressure and temperature. This information, in turn, may be used to predict the well performance. The methodology is similar to the Ramey/Whiting technique [14], but extended to include the effects of additional parameters and a comprehensive sensitivity analysis.

It cannot be overly emphasized, though, that reservoir performance predictions can only be suggested with data from one well. Several holes, judiciously determined in conjunction with geological data, are necessary for confident performance predictions. Furthermore, although virtually immediate speculations can be offered for obviously deficient wells, 30-year projections will not be possible unless a comprehensive well measurement program is undertaken. A three-month period per well is considered standard.

c. Physical Modelling

The physical modelling program can be divided into three phases: preliminary unpressurized model, preliminary pressurized model, and final pressurized model. The status as of August 31, 1975, can be summarized as follows:

<u>MODEL</u>	<u>SIZE</u>	<u>PRESSURE</u>	<u>TEMPERATURE</u>		<u>STATUS</u>
			<u>MAX.</u>	<u>PROBES</u>	
Preliminary #1	3 ft ³	Atmospheric	212°F	10	undergoing tests
Preliminary #2	3 1/3 ft ³	200 psi	382°F	23	fabrication nearing completion
Final	30 ⁺ ft ³	300 ⁺ psi	500 ⁺ °F	23	design initiated

It was decided that preliminary models be constructed for the following reasons:

- 1) Cost constraints - \$6,000 was available . . . a larger-sized pressurized model would have cost about \$10,000.
- 2) Safety regulations - OSHA standards limit the use of materials and require a specially licensed welder.

It is the intention of the program to proceed to the final pressurized model. Additional funding, though, will be necessary.

A photo of the unpressurized physical model can be found in Figure 3.1-7. A photo of the partially completed shell of the preliminary pressurized

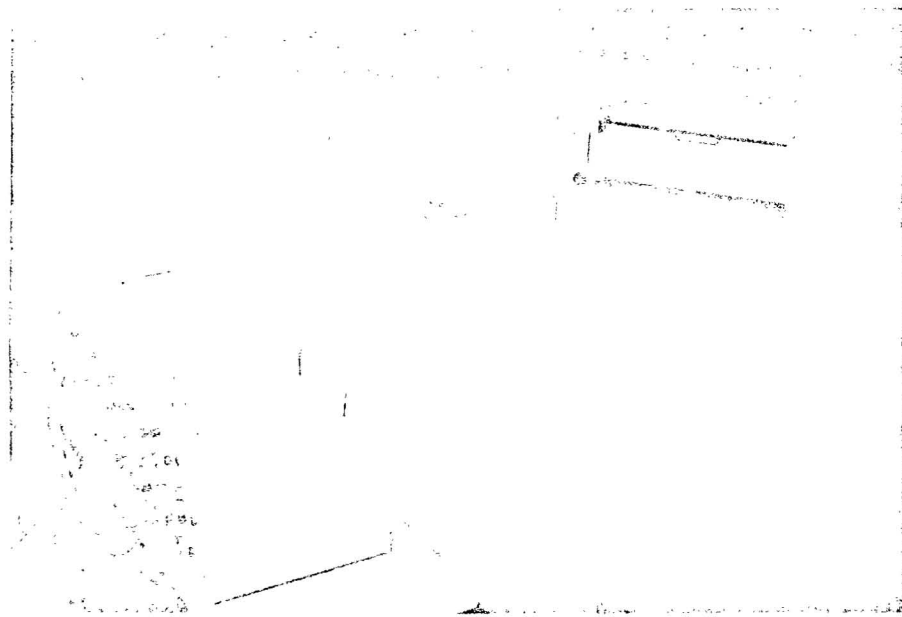


FIGURE 3.1-7 PHOTOGRAPH OF UNPRESSURIZED MODEL
WITH PERIPHERALS

model is located in Figure 3.1-8. A schematic diagram of the latter is shown in Figure 3.1-9. Figure 3.1-10 is a photo of the recorder and heater controllers.

The key components in addition to the tank are as follows:

- 1) Esterline Angus 24 point recorder using ten 1/4"D and thirteen 3/16"D resistance temperature detector (RTD) probes. The RTD's were selected because they are capable of withstanding high pressures, saline fluid conditions, and were immediately available at reasonable cost. It is possible that the size of the RTD's could somewhat disturb flow patterns for the preliminary models.
- 2) Stan-trol heater and controller sensor system capable of varying heater surface temperature between ambient and 1800°F. 1800°F is about the temperature of liquid magma. The total heat release capability is 6 kilowatts: two 2 kw and two 1 kw heater controllers. The heaters are convertible to any shape desired. A schematic of possible configurations is shown in Figure 3.1-11.
- 3) Haskel air driven hydraulic pump to simulate compressed water conditions.
- 4) Sanborn dual channel recorder for continuous pressure (and temperature) measurements.

The results of the tests from the physical model should be useful in the following ways:

- 1) A check can be made of fundamental information. For example, does convection initiate at a Rayleigh Number of 40?
- 2) Data can be obtained to aid the various computer models in refining predictive capability.
- 3) The concept of geothermal reservoir self-sealing can be investigated.
- 4) Reinjection can be tested.
- 5) One of the classical points of contention, "Is a geothermal reservoir an open or closed system?" can be studied.

A first report of the physical model runs will be available before the year (1975) is over. It is not expected, though, that any of the major issues, as listed above, will be investigated in detail until 1976.

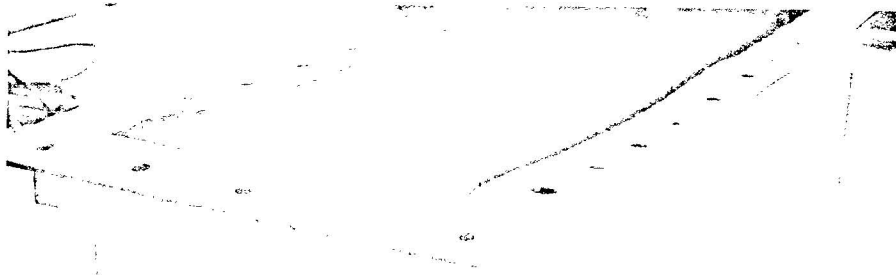


FIGURE 3.1-8 PHOTOGRAPH OF PRESSURIZED MODEL

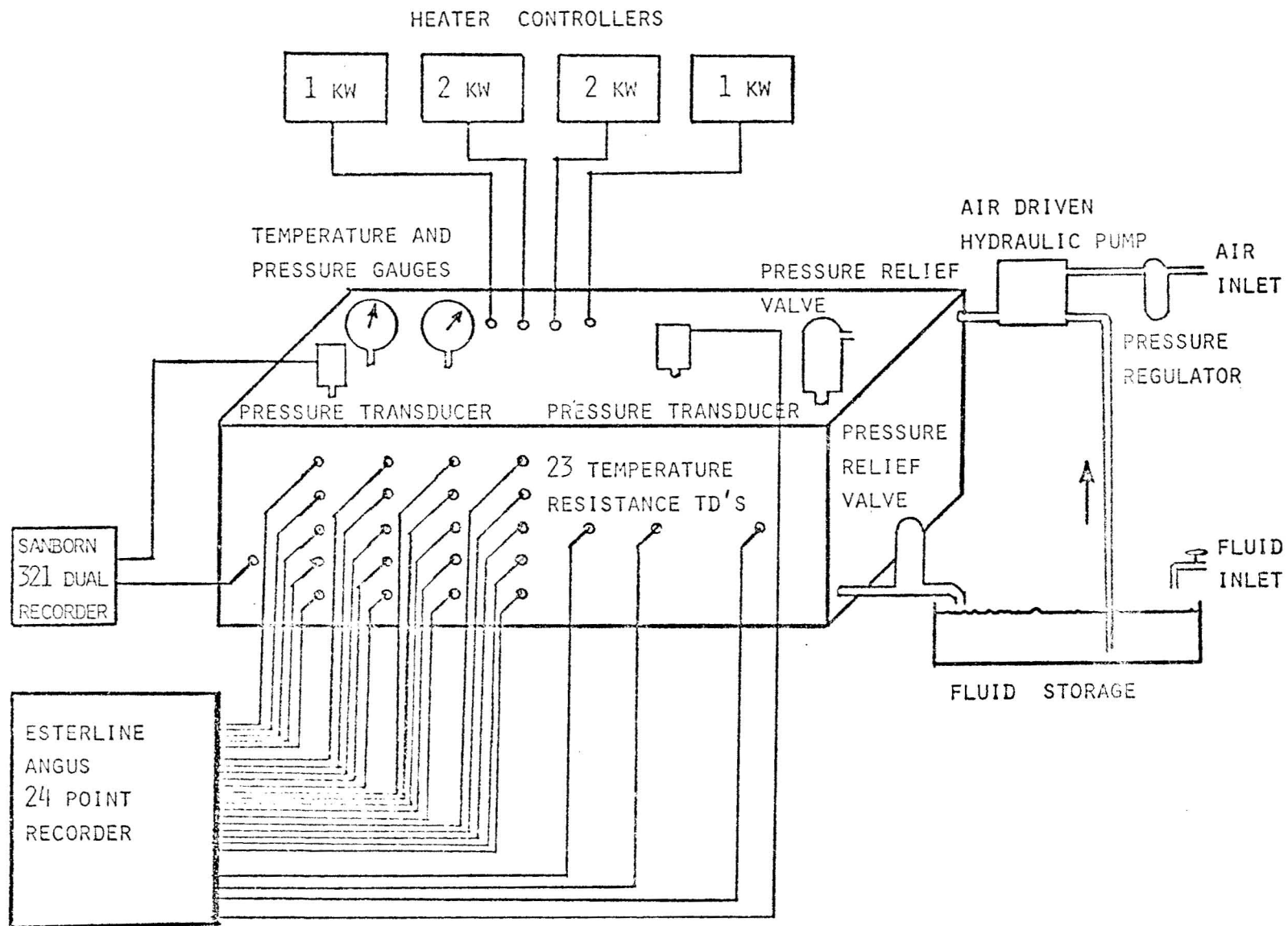


FIGURE 3.1-9 SCHEMATIC DIAGRAM OF PRESSURIZED GEOTHERMAL RESERVOIR PHYSICAL MODEL

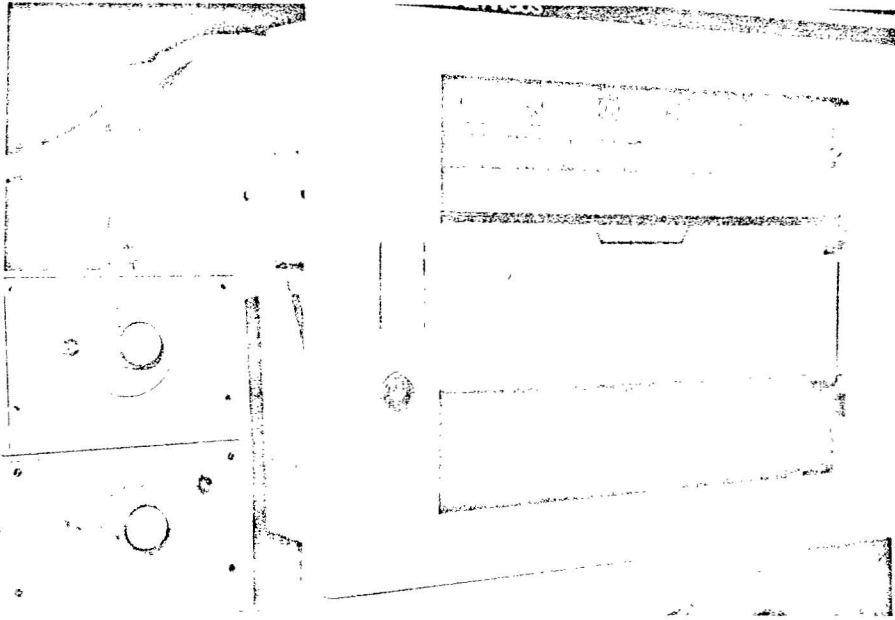
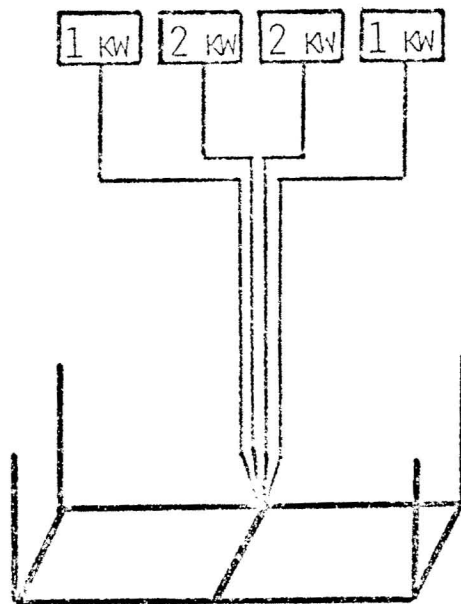
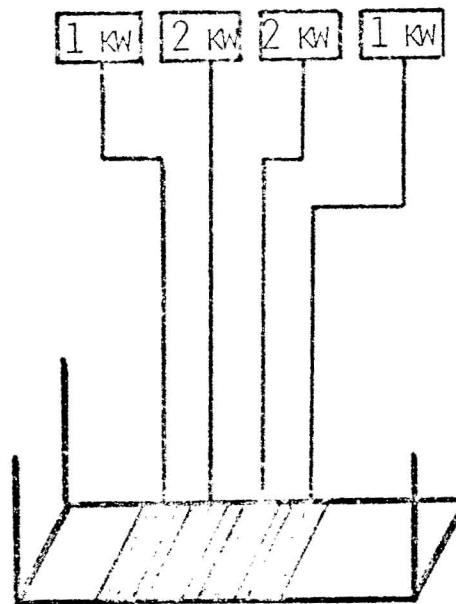


FIGURE 3.1-10 PHOTOGRAPH OF 24 POINT RECORDER
AND HEATER CONTROLLERS

POINT SOURCE IN 2-D MODEL
CENTERED AT BOTTOM OF
RESERVOIR



APPROXIMATE EXPONENTIAL
SOURCE CENTERED AT
BOTTOM OF RESERVOIR



VERTICAL DIKE HEAT SOURCE

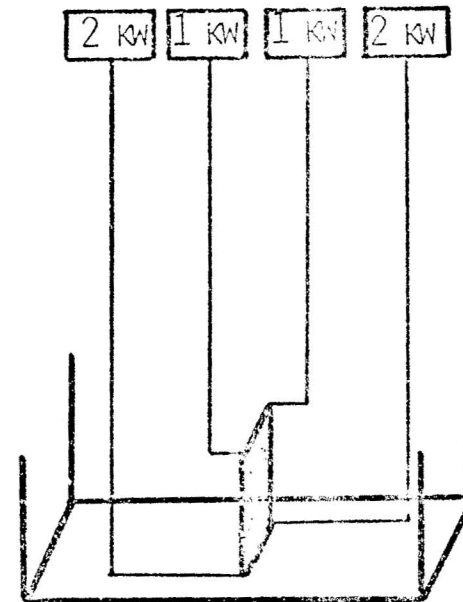


FIGURE 3.1-11 HEATING ELEMENT CONFIGURATIONS

C. Future Work

1. Numerical Modelling of Geothermal Reservoirs

During the next reporting period, numerical solutions for the problem of steady reinjection of fluids in a liquid-dominated geothermal reservoir will be completed. The numerical solutions for the problems of transient responses in geothermal reservoirs with pumping and reinjection as well as the dynamics of the Ghyben-Herzberg lens in a geothermal reservoir will be initiated.

2. Well Test Analysis and Physical Modelling

Activity is continuing in three related areas: 1) well test measurement, 2) analysis of well data, and 3) physical modelling. It is expected that all three areas will come to a phase two conclusion early next year. Future work will be dependent on additional funding.

a. Well Test Measurement

Efforts at detailing hardware and operational costs are nearing completion. It is imperative that funds be identified for the well measurement program. At this time, cutbacks in the budget have totally excluded this phase of the operation. The general thinking has been that measurement can be seriously considered after a worthy geothermal reservoir is found. Training of local personnel is also a point of concern. In summary, so that well measurement can be consummated, hardware must be purchased and personnel must be trained. The contracting of these services out to private companies will involve expenses several times larger than if accomplished in-house.

b. Well Analysis

A computer program to predict well performance is nearing completion. The program will ultimately be capable of handling geothermal reservoirs of all types: vapor or liquid-dominated, flashing within the reservoir, closed or open system and various salinities. The initial program will be tested with New Zealand measurement data.

c. Physical Modelling

Tests on the unpressurized model are coming to a conclusion. Experimental runs are being planned for the preliminary pressurized model and design of the final pressurized model is being initiated. The concept of self-sealing will be explored in the final pressurized model.

TASK 3.1 GEOTHERMAL RESERVOIR ENGINEERING

D. References

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TASK 3.6 OPTIMAL GEOTHERMAL PLANT DESIGN

Investigators: H. C. Chai, J. Chou, and D. Kihara

A. Timetable

- | | |
|--------------------|---|
| June 30, 1975 | <ol style="list-style-type: none">1. Heat exchanger design--check out test set-up and extend analysis of heat exchanger specifications as input parameters are changed2. Construct components and assemble experimental heat transfer loop |
| September 30, 1975 | <ol style="list-style-type: none">1. Establish general requirements, ground rules, and design criteria for a research-oriented plant for liquid-dominated fields2. Construct and test horizontal heat exchanger |
| December 31, 1975 | <ol style="list-style-type: none">1. Set up procedures for the design and selection of the components of regenerative binary fluid plants2. Continue testing of horizontal heat exchanger and write computer program for horizontal heat exchanger3. Complete conceptual design of a prototype research plant for assisting a mechanical engineering contractor to complete the final design4. Binary-fluid cycle research--survey the availability of components to be used with each working fluid |
| June 30, 1976 | <ol style="list-style-type: none">1. Lay out detailed flow diagrams of the plant based on a regenerative binary fluid system, with a vapor flashing system as the alternative2. Analyze test data for horizontal heat exchanger and begin testing of vertical heat exchanger |
| December 31, 1976 | <ol style="list-style-type: none">1. Estimate capital costs of the plant, evaluate unit operating cost, and compare feasibilities of the two systems2. Complete testing and analyze test data for vertical heat exchanger |

TASK 3.6 OPTIMAL GEOTHERMAL PLANT DESIGN

B. Progress to Date

1. Conceptual Study of a Research-Oriented Plant

Based on extensive geological surveys, the geothermal resources in Hawaii are probably hot brine. The probability of finding an adequate reservoir is high enough that an advanced planning for a relevant power plant is warranted, although the decisions on the main features of the plant cannot be made until the resources are proven. Since there has never been a geothermal plant built in the 50th State, it would be prudent to construct a research-oriented plant first. The purposes are to provide facilities for testing new plants of unconventional design and to experiment with the components of conventional vapor-flashing plants. Thus, the economic implication, environmental impact, and operational reliability of innovative plants can be accurately evaluated. As most of the known geothermal fields in this country are liquid-dominated, the results will be beneficial not only to the State of Hawaii, but to all of the United States. During the past period, a part of the effort was applied to the conceptual study of research-oriented plants.

Consideration has been given to the size of the experimental plant. It must be large enough to experience all the problems of a production plant. For the assessment of long-term capabilities of a new reservoir, the size must fit the optimal production rate of brine from one well at least. On the other hand, an unnecessarily large plant might become very wasteful. The probable size is suggested to be in the range of 5 to 10 Mw.

The vapor-flashing system, being well-developed in New Zealand and Japan, has been proven to be reliable and economically viable. In order to become familiar with its development, the designs of this system and its components were reviewed last year [1].* The most critical component of a plant which extracts power directly from the vapor of brine is the prime mover, usually a low-pressure steam turbine. Further research on the prime mover could significantly improve the plant performance. The research-oriented plant, which receives a mixture of vapor and liquid through a single pipe, shall be designed to retain the flexibility for testing innovative prime movers. The present study finds that one of the promising prime movers is the helical rotary screw expander, which has already been successfully tested at Lawrence Livermore Laboratory [2].

*Task 3.6 References are listed on page 40.

The binary fluid system is undergoing rapid development, and its future largely depends upon the successful development of heat exchangers which can be free of the fouling problem on the brine side. In the early part of the present study, attention was directed to the design of a liquid-to-liquid heat exchanger with mercury as the heat carrier. Technically it can be done by spraying mercury into hot brine and then pumping the mercury to a vessel in which the mercury directly comes into contact with the working fluid such as isobutane; however, further work was discouraged by the high cost of mercury, \$21 per pound, and by the complication of its chemical reaction with hydrogen sulfide in brine. Later, a study was made on the application of conventional shell-and-tube heat exchanger to transfer heat from brine to isobutane with inhibited acid for periodic cleaning. The detailed discussion on such application shall be given in a later report.

In a previous study [3], it was proposed to add a regenerative heat exchanger to the basic isobutane binary cycle. The exhausted brine of a regenerative cycle contains much more heat than that of a basic cycle. If there is need for the heat at low temperatures for industrial processing, adoption of a regenerative cycle could be economically attractive. The study of the design of a regenerative heat exchanger is in progress. With finned tubes, an overall heat transfer coefficient of 200 Btu per hr per sq ft of tube surface can be achieved. It appears that a regenerative binary plant is technically feasible.

2. Working Fluid Selection and Heat Exchanger Design

A parametric study was conducted of a vertical, counterflow, shell and tube heat exchanger designed for use in a 10 Mw geothermal power plant which utilizes geothermal brine at moderate temperatures [4]. The hypothetical power plant is based on conditions that may be encountered at a typical drilling site on the island of Hawaii.

Brine	350°F
Available cooling water	80°F
Efficiency of turbine-generator	85%
Efficiency of pump	75%
Working fluid velocity	7 ft/sec
Tube sheet	1 inch diameter with tube pitch of 1.1 on a triangular arrangement

Following a preliminary screening process, candidate working fluids were selected from two groups with similar chemical structures; isobutane as being representative of hydrocarbons, and Refrigerant-114 from the halogenated hydrocarbons, and characteristics of the Rankine cycle and primary heat exchanger were determined using these two fluids.

Detailed in graphical form are the results showing how (a) the required brine flow rate, (b) tube lengths, (c) number of tubes, and (d) pressure drops are affected by changes in working fluid, turbine inlet temperature, system pressure (subcritical and supercritical), and scale thickness.

In Figure 3.6-1, for all turbine inlet pressures, the required working fluid flow rate decreased as turbine inlet temperature is increased. However, it is to be noted that the decrease is more pronounced for supercritical pressures. Figure 3.6-2 shows that a minimum brine flow rate occurs at supercritical pressures for both fluids.

The minimum tube length occurs at a subcritical pressure and a turbine inlet temperature of approximately 300°F, for both fluids. In the turbine inlet temperature range 280-320°F, the tube length curve for each fluid is almost flat, indicating a slight variation of tube length with increasing turbine inlet temperature (see Figure 3.6-3).

In terms of the amount of tube material or total heat transfer surface area required, the subcritical pressures for both fluids require substantially less material (see Figure 3.6-4). The smaller number of tubes due to lower working fluid flow rate and the shorter tube lengths account for the smaller amount of tube material.

The total shell-side pressure drop for the subcritical pressure case is approximately constant for both working fluids. However (from Figure 3.6-5), the pressure drops for R-114 are seen to be much larger than those for isobutane. At supercritical pressures, the total shell-side pressure drop for each fluid is lower than for subcritical pressures. The larger pressure drops for R-114 are a result of higher density and flow rates.

To determine the effect of scale thickness on heat exchanger design and working fluid selection, a turbine inlet temperature of 280°F and a subcritical pressure were selected. The resulting tube lengths and shell-side pressure drops are shown in Figure 3.6-6.

In general, this study showed that the minimum brine flow rate for each working fluid occurred at a supercritical pressure. However, the tube lengths

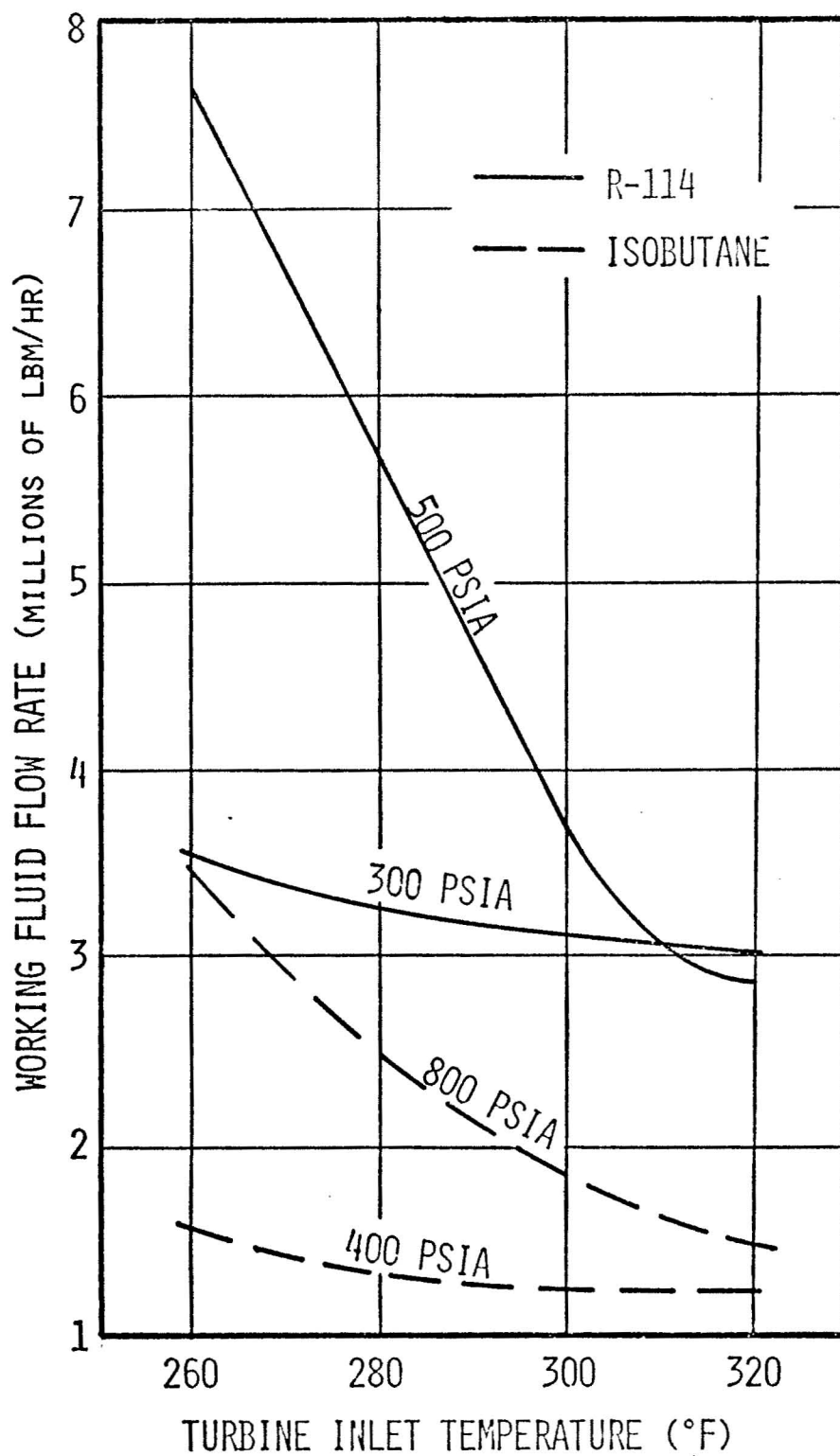


FIGURE 3.6-1 INFLUENCE OF TURBINE INLET TEMPERATURE AND PRESSURE ON FLOW RATE OF WORKING FLUID

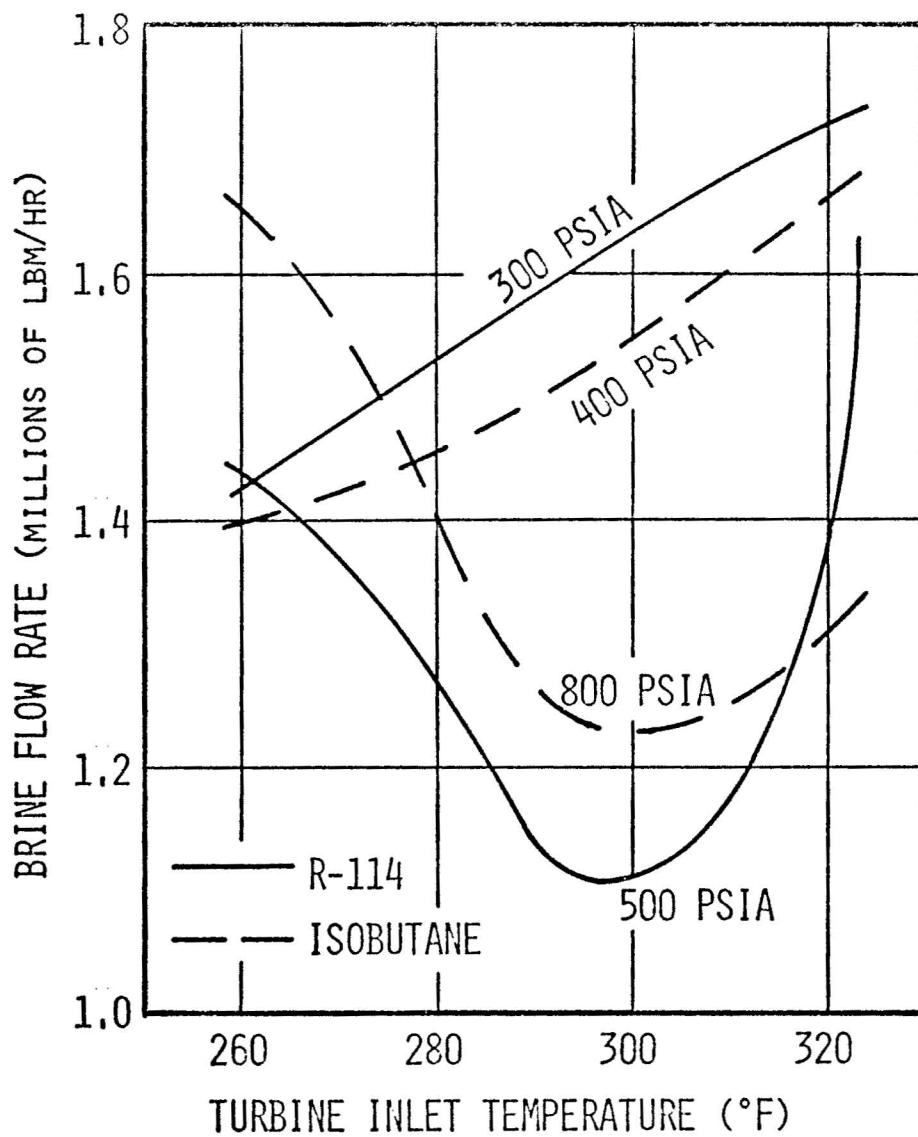


FIGURE 3.6-2 INFLUENCE OF WORKING FLUID, TURBINE INLET TEMPERATURE AND PRESSURE ON FLOW RATE OF BRINE

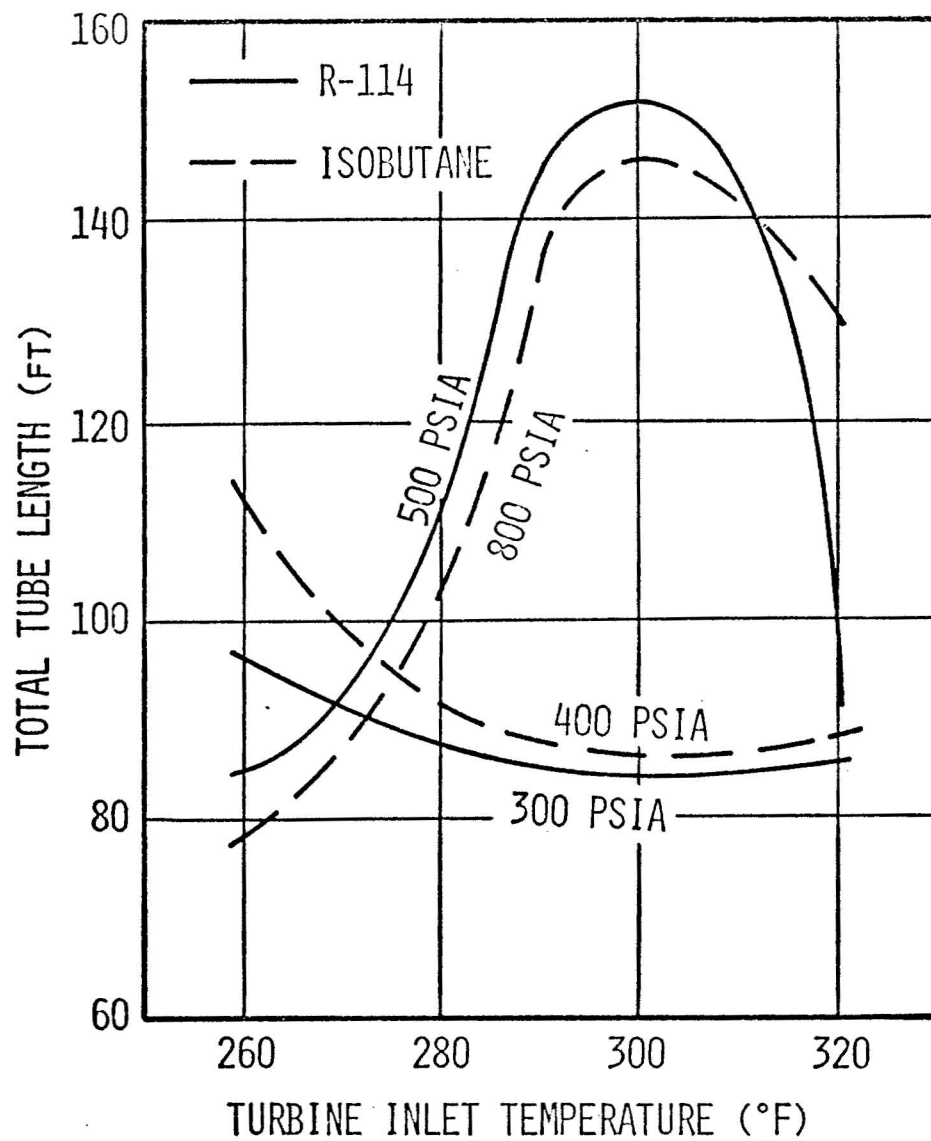


FIGURE 3.6-3 INFLUENCE OF WORKING FLUID, TURBINE INLET TEMPERATURE AND PRESSURE ON TOTAL TUBE LENGTH

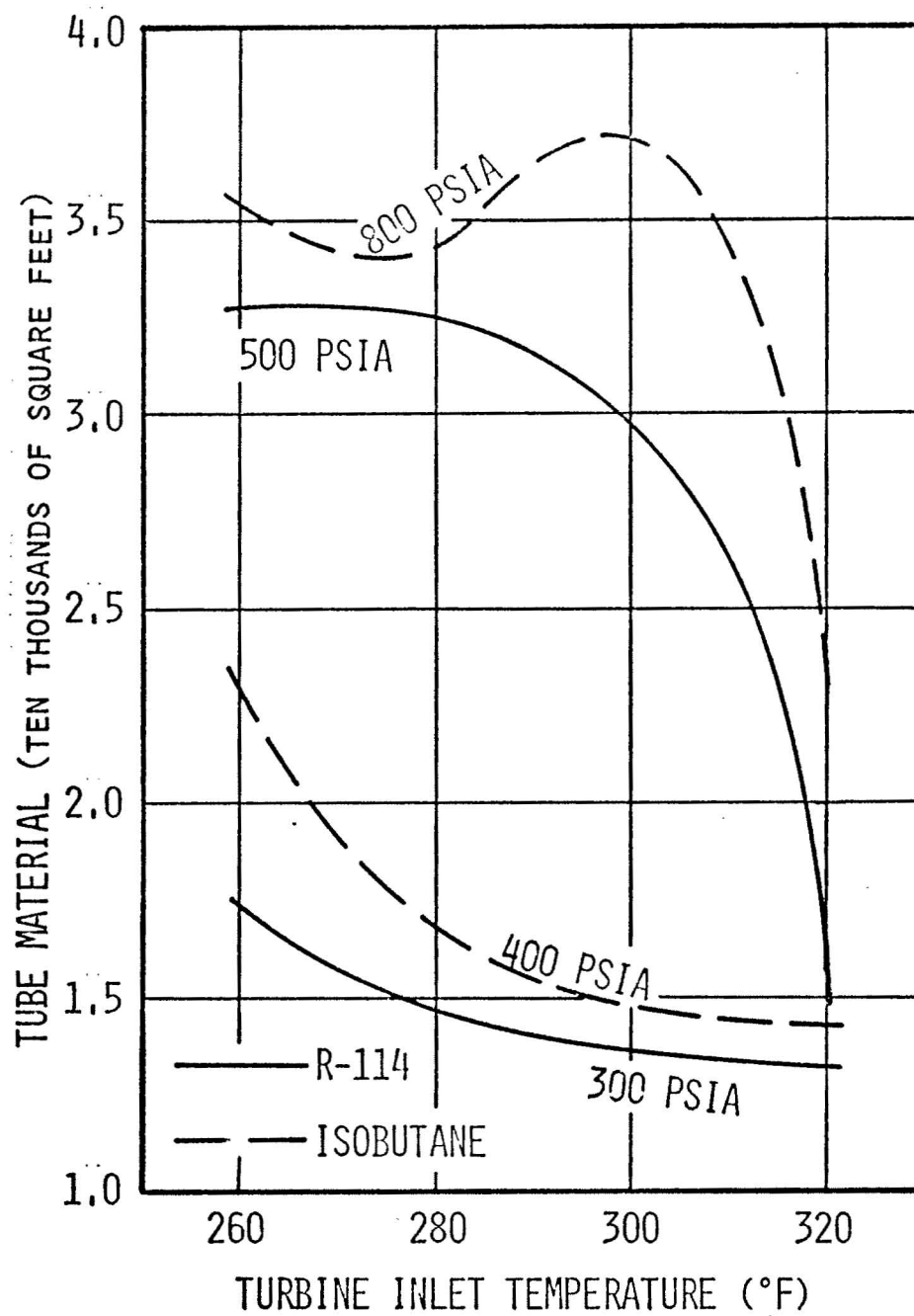


FIGURE 3.6-4 INFLUENCE OF WORKING FLUID, TURBINE INLET TEMPERATURE AND PRESSURE ON TUBE MATERIAL REQUIRED

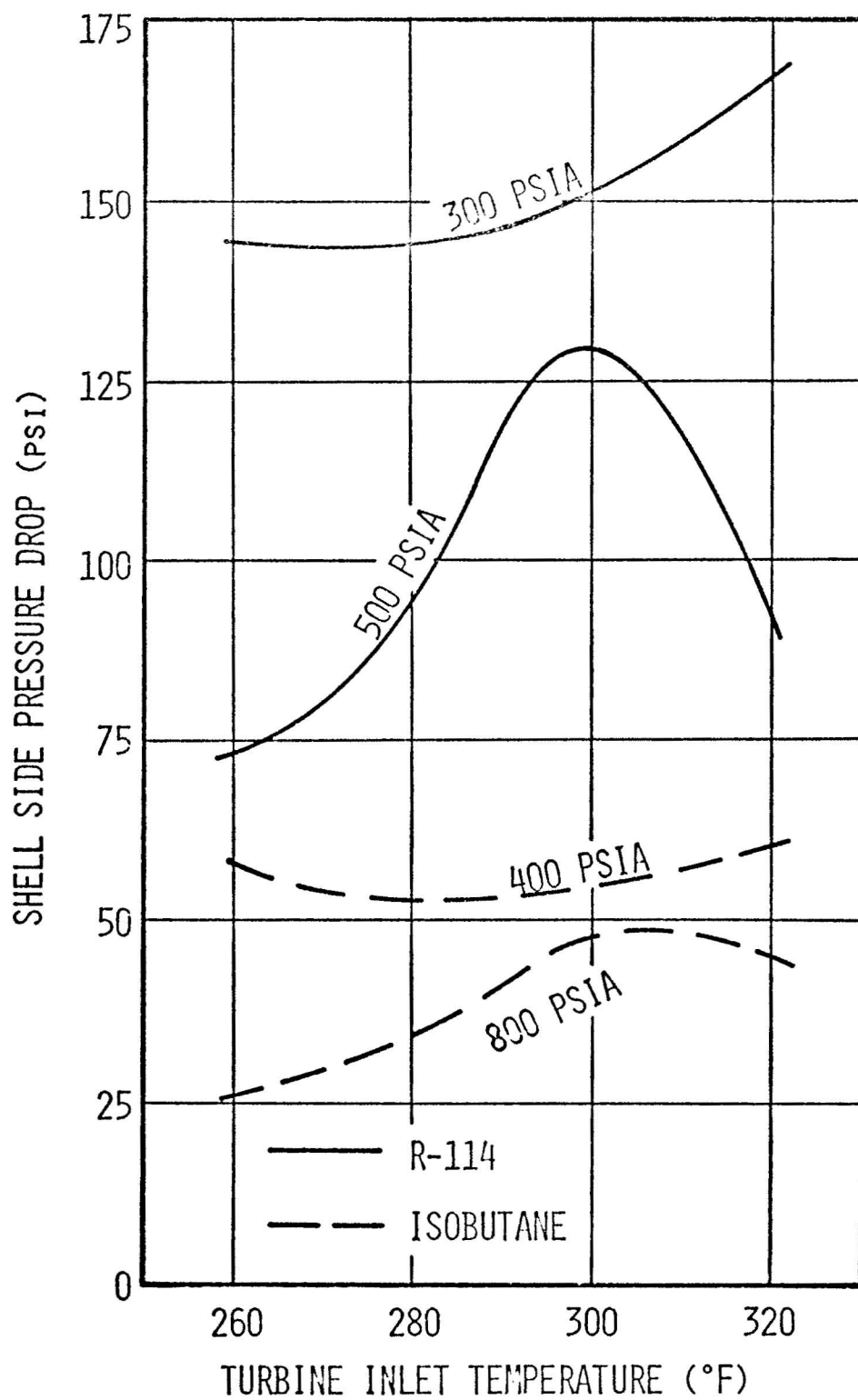


FIGURE 3.6-5 INFLUENCE OF WORKING FLUID, TURBINE INLET TEMPERATURE AND PRESSURE OF SHELL SIDE PRESSURE DROP

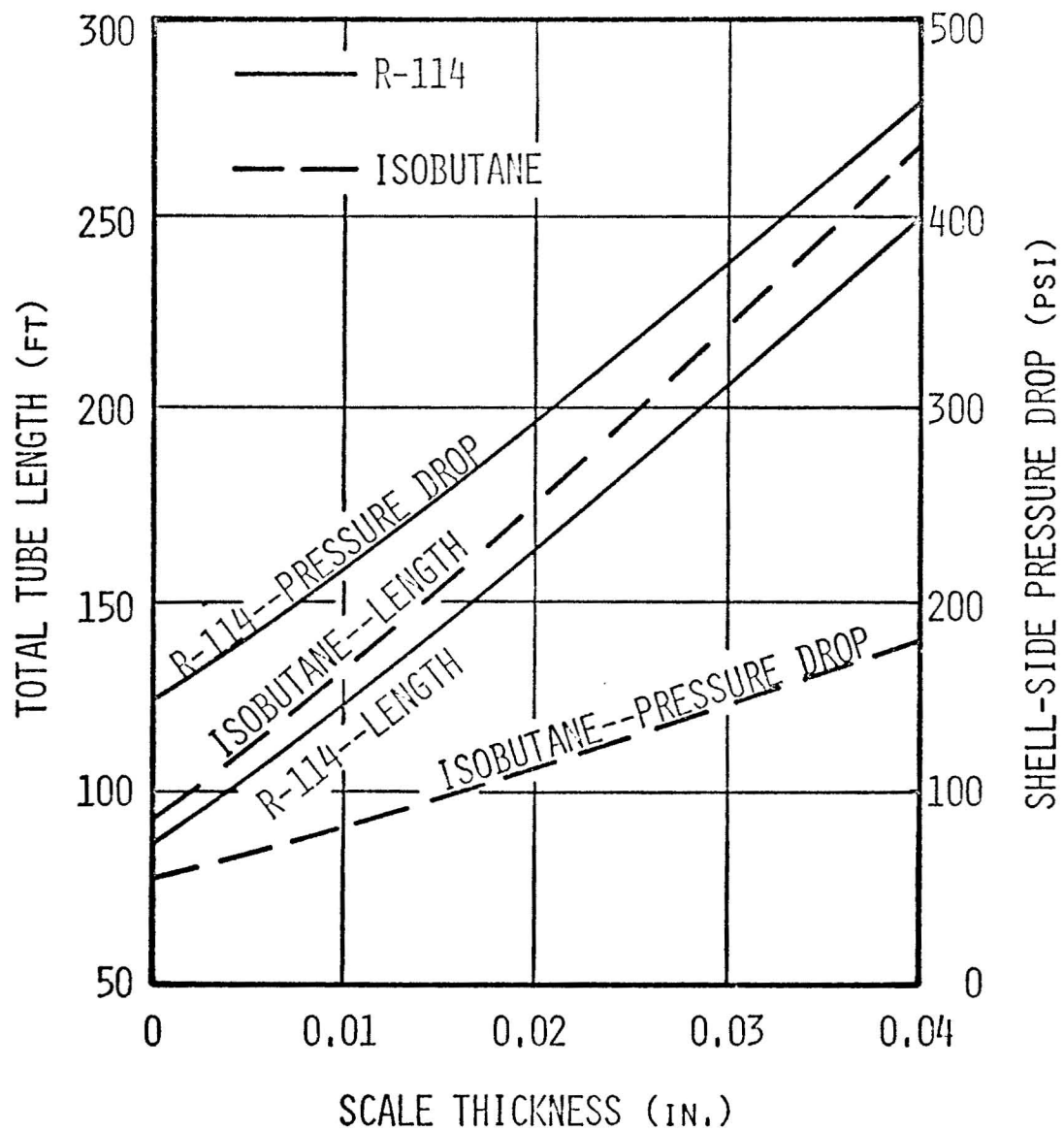


FIGURE 3.6-6 INFLUENCE OF SCALE THICKNESS ON TOTAL TUBE LENGTH AND SHELL SIDE PRESSURE DROP

for these turbine inlet conditions were at a maximum. The tube lengths for the subcritical system pressures were substantially less but resulted in larger pressure drops.

3. Experimental Test Loop for Heat Exchanger

The design of an experimental test loop to study the heat transfer and pressure drop characteristics of Freon-11 on the outside surface of a tube bundle has been completed. The front elevation view of the loop is shown in Figure 3.6-7. The loop is so designed that the following test parameters can be varied: heat input, fluid velocity through the bundle, inlet condition of fluid, pitch to diameter ratio of the heating rods, and orientation of test section. The valves are arranged in such a way that any section of the test loop can be removed for repairing. Also, the volume and the location of the liquid receiver is such that all the Freon in the loop can be drained and stored. Initially, it was planned to insert the tube bundle in a Pyrex glass cylinder so that the flow patterns of the Freon could be observed, but this idea was dropped and stainless steel was used because of the low allowable stress of the Pyrex glass. Also, the size of the heater was reduced from the size previously reported (without changing the pitch to diameter ratio), so that a smaller Freon pump could be used.

All the components of the loop (except the Freon pump) have been received. Some of the major components received are as follows:

- a. Constant voltage transformer: capacity of 13 KVA
- b. Variable voltage transformers: capacities of 28.5 amperes and 30 amperes
- c. Water chiller: 3 ton cooling capacity
- d. Condenser: 15,000 Btu/hr capacity
- e. Liquid receiver: volume of 10 cubic feet
- f. Six channel digital indicator capable of reading temperature 0 - 400°F and flow rate 0 - 29 GPM, plus 4 open channels
- g. Digital multi-meter (3-1/2 digits) 2 units, voltage: 0-500 volts, current: 0-50 amperes with shunt
- h. Heaters (Incoloy heating rods): outside diameter of 0.315 inches, length of 24 inches, heating capacity of 30 watts/sq. inch

All the instruments except the direct measuring instrument for density or void fraction of two-phase flow have been procured. It appears that no

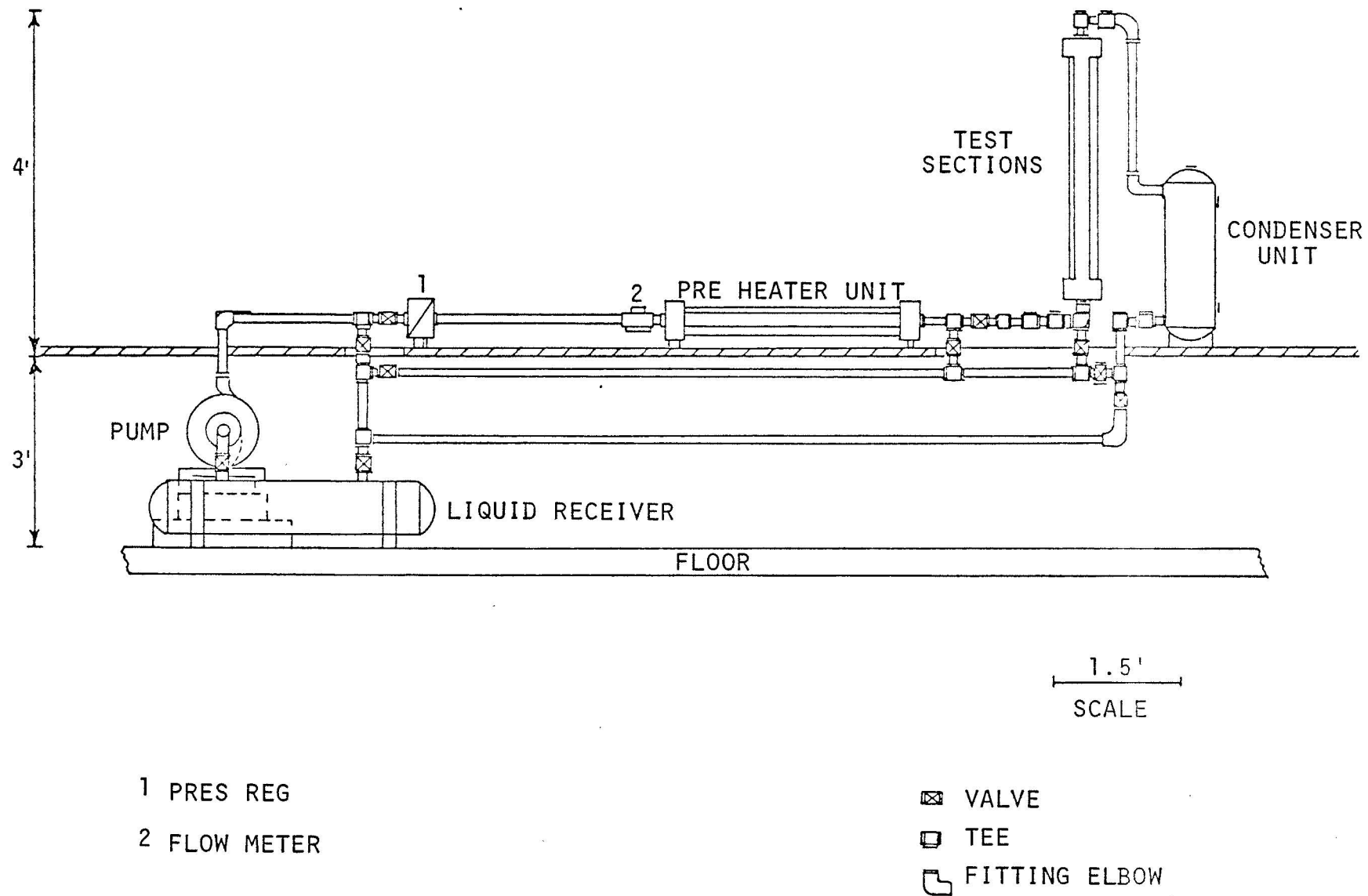


FIGURE 3.6-7 FRONT ELEVATION VIEW OF EXPERIMENTAL TEST LOOP

reliable commercial instrument is presently available at a reasonable price. Therefore, the exit condition of the Freon will be computed from the heat input and by using a guarded heater to eliminate heat loss from the test section.

Testing of the loop will be initiated as soon as the Freon pump is received.

C. Future Work

During the next reporting period, the following work will be undertaken:

1. Continue with conceptual design of a prototype research plant, examining in detail several variations, e.g., pumped vs. self-flowing well, basic vs. regenerative cycle.
2. Complete assembly of experimental test loop and begin testing of heat exchanger.

TASK 3.6 OPTIMAL GEOTHERMAL PLANT DESIGN

D. References

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